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THE APPLICATION OF DIGITAL SHIFT REGISTERS TO ACTIVE CORRELATIO--ETC(U)

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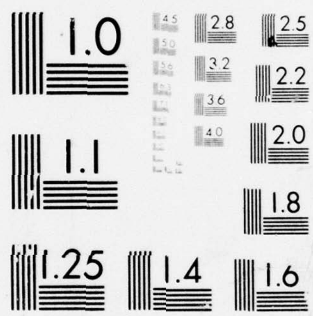

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Foreword

This memorandum has been prepared for the information of others working in allied fields at NEL [redacted].

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The Application of Digital Shift Registers to Active Correlation Sonar

Introduction

The development of the shift-register type pseudorandom noise generators[1] (PRNG's) for use in broadband active correl-

1. W. B. Allen and F. J. Smith, Pseudorandom Noise Generator, NEL Technical Memo. No. 36. (Confidential)

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ation sonar solved the major problem of obtaining the long delay times necessary to bring the reference signal into correlation with the water borne signal. This was achieved by using two identical PRNG's which put out identical trains of pseudorandom pulses so that the delay time needed was obtained by starting the second PRNG at a later time than the first one. Corrections to the delay time were obtained by sweeping the delayed reference signal by means of a resolver. However, since rapid sweep by this method did not permit sufficient integration time, the problem of searching or scanning through large changes in range in a relatively short time remained unsolved.

One of the obvious solutions to this problem is the use of a tapped delay line and a correlator for each tap; the number of correlators and the delay between them being chosen to give the desired range increments and total range to be searched. A second method is a matched filter or code synchronizer[2]

2. Willis Jackson, Communication Theory, Academic Press, New York, (1953), p 273.

capable of unambiguously recognizing a special sequence of

binary digits and effectively pin-pointing their origin in time.

Digital Shift Register Delay Lines

While using the digital shift register PRNG's in broadband correlation sonar, it soon became apparent that the shift register is a delay device and can be used directly as a tapped delay line for the PRNG signals. With proper sampling it may also be possible to extend their use as tapped delay lines for any type of signal. In the case of PRNG signals, however, a shift register of suitable length is operated with the first n stages coupled as a PRNG and the remaining stages transferring the sequence along the line and making it available at a later time at each successive stage. The time delay for each stage in a digital shift register will depend on the shift pulse frequency. A frequency of 1 kc will give a 1 millisecond delay per stage, while a 100 cps frequency will give 10 milliseconds delay per stage.

For very broadband signals the PRNG's are usually operated at a shift pulse frequency of 4 times the center frequency of the desired signal band, since the PRNG output has a uniform spectrum only to approximately one half the driving frequency, as can be seen in Figure 1. Under these operating conditions each stage of the shift register will give a delay of one-quarter wave length of the center frequency of the signal band. A more economical way of operating a PRNG and associated delay stages in terms of total available delay time is to drive them at a frequency which is lower than the center frequency of the desired broadband signal. The desired signal band can be ob-

tained from one of the upper maxima in the PRNG spectrum, see Figure 1, or the frequencies below ½ the driving frequency can be heterodyned to the desired frequency range. Each shift period, i.e., unit of delay, is then greater than the period of the center frequency of the signal band. For example, if an 850-950 cps signal bandwidth were to be utilized and the PRNG were driven at 200 cps, each stage of the shift register would give a 5 millisecond delay or 4.5 wavelengths at the center frequency of the signal. By using the above method relatively long delays can be obtained with reasonably short shift registers, although at the expense of a narrowing of the available signal bandwidth, since the region of the uniform spectrum in the PRNG output is reduced proportionately as lower frequency driving signals are utilized.

Multiple Correlator

The multiple correlator consists of a delay line with uniformly spaced taps and individual correlators such that one can increase the search rate by simultaneously correlating the input signal with the local signal for several different time delays, see Figure 2. The PRNG reference signal S is fed into the multi-tapped delay line which is the digital shift register driven at a frequency such that the desired delay per stage is obtained. The outputs S_1, S_2, ...S_n from the successive taps are delayed replicas of the reference signal. Each delayed replica is fed into an individual correlator which continuously multiplies the delayed signal with the received signal E and time averages the instantaneous product to give one point on the correlation function. From Figure 2b it can

be seen that with exact time coincidence, i.e., perfect correlation as represented by E and S_i, the resultant product will always be positive which yields the maximum peak on the correlation function.

The spacing of the points on the correlation function obtained from the multiple-correlator depends on the delay per stage. If the delay per stage is equivalent to a large range interval only a few points on the correlation function will be obtained and consequently the reference signal will have to be swept with respect to the received signal in order to obtain the complete correlation function. However, if the delay per stage is small enough ($\frac{T_o}{8}$, where T_o is the period of the center frequency of the band) a sufficient number of points will be obtained such that the correlation function will be adequately described by the points.

Matched Filter

The matched filter here considered is a digital system which detects the group synchronization of a sequence of pseudo-random binary digits. The filter has one tap for each binary digit and the final output signal is the properly phased sum of all these outputs. In operation the signal which results is a cross-correlation function.

If we compare the matched filter with the usual correlation system, we see that the reference signal is built into the matched filter thereby making it possible to obtain essentially the same output without separately generating a reference signal. The matched filter is matched to the signal sequence, e.g., as generated by an n stage PRNG, by having one tap corres-

pond to each binary digit in the signal; the signs of the taps are reversed for those digits which are "-1". Therefore, when the correct signal sequence is synchronized in the filter, the negative digits are changed to positive ones and every tap registers a " +1", see Figure 3, which on summing gives $N = 2^n-1$ as the final filter output. As a signal advances through the filter, the output at any instant is a point on the finite-cross-correlation function, because the signal is operated on by the filter giving an equivalent multiplication as if by a reference signal, and summing the taps gives an average over N simultaneous samples.

The output obtained by a graphical solution of a filter matched to the signal generated by a four stage PRNG (15 digits) is shown in Figure 4. This would be the output from a 15-tap delay capable of handling +1, 0, -1, (this includes the usual delay lines such as electrical networks, magnetic drums, etc.,) and was plotted assuming a zero for any tap not occupied by a digit of the signal sequence.

Digital shift registers seem very suitable for use as a matched filter because each stage provides two outputs which have a 180° phase difference (i.e., opposite signs). However these matched filters give a slightly different result than the usual delay line since the shift register has only two states; its output can be +1, -1; +1, 0; or 0, -1 depending upon the reference point. The output from this type of filter (with -1, +1 states) matched to the signal from a 4 stage PRNG was solved graphically and is shown in Figure 5 assuming all stages to be in a " +1" state when a signal is fed into the

register. The output function is not symmetrical as is the output from the delays which have 3 possible states.

An n stage binary system has 2^n possible combinations of "+ 1" and "-1" taken n digits at a time. The algebraic sum of the states of one stage over the 2^n combinations is zero since each stage has an equal number (2^{n-1}) of "+ 1" and "-1" states. Now if one of the combinations which is a "-1" state for this stage is eliminated the algebraic sum will no longer be zero but "+ 1". In an n stage PRNG all possible combinations of an n stage binary system occur except the all "-1" combination; therefore, the algebraic sum of all the states for any stage over the 2^n-1 combinations is "+ 1". A matched filter operating on the output of a PRNG has 2^n-1 taps which simultaneously observe all the states which occur at a single stage of the PRNG and since the all "-1" combination is excluded there will be one more "+ 1" tap than "-1" taps (the "-1" taps reverse the sign of the digit observed). Therefore, a matched filter for a PRNG signal will have a constant "+ 1" output when the input is continuously "+ 1" since 2^{n-1} taps sum as "+ 1" and 2^{n-1}-1 taps sum as "-1"; similarly the output will be a constant "-1" when the input is continuously "-1" since 2^{n-1} taps will sum as "-1" and 2^{n-1}-1 taps sum as "+ 1".

In graphically solving for the output of matched filters operating on PRNG signals it was found that when one sequence follows another the output is a constant "-1" for the digits between the times of exact synchronization. The complete output consists of positive pulses with an amplitude of 2^n-1 units occurring at intervals of 2^n-1 digits with a constant "-1" level

for the 2^n-2 digits between the pulses.

In operation the matched filter multiplies the signal sequence digit by digit with an identical signal and the output is the instantaneous sum of all these products. The sequences generated by PRNG's have the property that this digit by digit multiplication of two identical sequences yields all "+ 1's" and sums to 2^n-1 if the two sequences are exactly synchronized. If the two sequences are displaced by one or more digits and one sequence folded, i.e., a digit dropped from the last stage is simultaneously fed into the first stage, multiplying digit by digit results in a sequence the same as the original sequence with all digits changed to the opposite sign and a resultant sum of a "-1". This result holds true for any relative displacement of the sequences generated by 2, 3 and 4 stage PRNG's and also for spot checks with the signal from a 7 stage PRNG. No rigorous mathematical reason or proof has been derived for this result but it appears to be a property of the PRNG sequences and it is felt that it will hold for a PRNG with any number of stages.

A gaussian noise input to a matched filter will produce on the average an output proportional to $\sqrt{n}$.

Matched Filter Systems

A matched filter employing a digital shift register requires that after transmission and reception of the signal the information must be restored to a sequence of rectangular pulses to be fed into the matched filter. Several techniques to achieve this should be possible. Difficulties arising from doppler

and multiple-path interference, however, seriously limit some methods. The methods which have been considered are (a) heterodyning the bandwidth necessary to preserve a low frequency sequence generated by a PRNG to a band that can be transmitted and upon reception restored to the original band, (b) FM or AM modulating a carrier with the PRNG output and demodulating after reception and (c) transmitting a broadband signal generated by a PRNG; clipping the signal at the receiver and detecting it with a filter designed to match the signal after it has been limited by clipping.

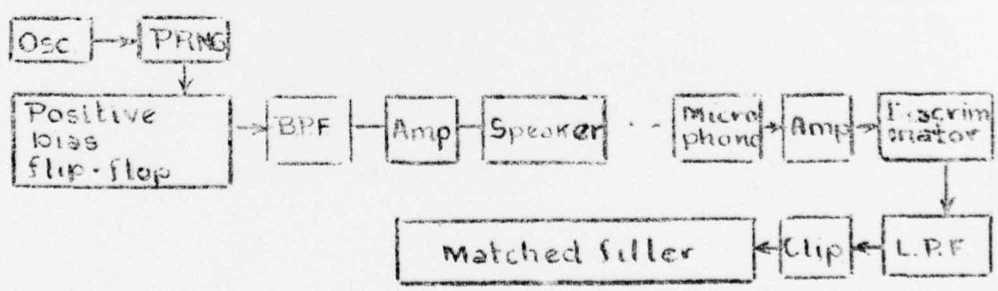
The most serious difficulty with the first method would be the magnification of any doppler when the transmitted band is heterodyned back to the original sequence. The second method would suffer seriously in the presence of interfering multipaths. The third method therefore, seems to offer the most promise of a satisfactory system. The disadvantage of this method is the need for a much greater number of binary stages to adequately match the clipped signals.

The major problem in using a matched filter is the doppler frequency shift. Considering doppler as an expansion or contraction of the signal sequence by the lengthening or shortening of the individual pulse periods, it appears that doppler can be handled by multiple combinations of outputs from a single digital shift register or delay line. Each increment of doppler would require a set of properly spaced taps, which are compressed or expanded versions of the spacings required for the undopplered signal.

Experiments

A matched filter using a digital shift register has been built and tested in the laboratory. This unit consisted of a 15-stage shift register with taps arranged to match the signal from a four stage PRNG. The output of the filter for a single sequence of pulses and for a series of sequences is shown in Figure 6. These traces were obtained with the output of a PRNG being fed directly into the filter and the system operated slowly enough so the output during each shift period could be distinctly seen. Comparing Figure 6a with Figure 5 it can be seen that the base line of Figure 6a occurs at " +1", which is as predicted since the filter input was continuously " +1" preceding and after the signal sequence. In Figure 6b, where a series of 8 sequences was passed through the filter, the level preceding the series is " +1" and the base line during the series is "-1" as predicted from the graphical solution. The slight irregularities in the "-1" base line are due to differences in the load resistors resulting in slightly different tap voltages which fail to sum to precisely "-1".

A further experiment with the 15-stage matched filter consisted of a modulation system operating in air. This is shown in block diagram below:



This system utilized a 4250 cps carrier and the modulation consisted of shifting from 4000 to 4500 cps as the PRNG output varied from "+1" to "-1". The oscillator output was bandpass filtered to 3400-4800 cps. This signal was then transmitted. After reception, amplification and discrimination the signal was lowpass filtered with a 125 cps cutoff. The resulting signal was limited and fed into the matched filter. Figure 7a, b, c, d, and e show typical resulting records for various speaker-microphone spacings which varied the multipath interference and the signal-to-noise into the receiver. In this application the PRNG was operating at 125 cps so that the recorder could not precisely follow the output waveform.

Figure 7a was obtained with a very short transmission path of the order of 4 feet and shows no significant multipath interference or noise. Figure 7b shows a trace with what appears to be a consistent multipath interference. Figure 7c and 7d are traces obtained with transmission path lengths of the order of 15 feet and have considerable multipath and noise interference. Figure 7e is a record of the same condition with slow paper feed showing the variability of the output as the signal was distorted by noise and changing conditions in acoustic path (people walking across the path, etc.). During these tests no measurement was made of the S/N or the extent of the multipath interference, the traces are shown only to show typical results to be expected.

Conclusions

A digital shift register should operate satisfactorily as a matched filter in the detection of pseudorandom signals for

a correlation sonar. It appears that a filter designed to match a known signal after clipping should be the most satisfactory system. Doppler can be handled by properly spaced sets of taps from a single filter, one set for each increment of doppler.

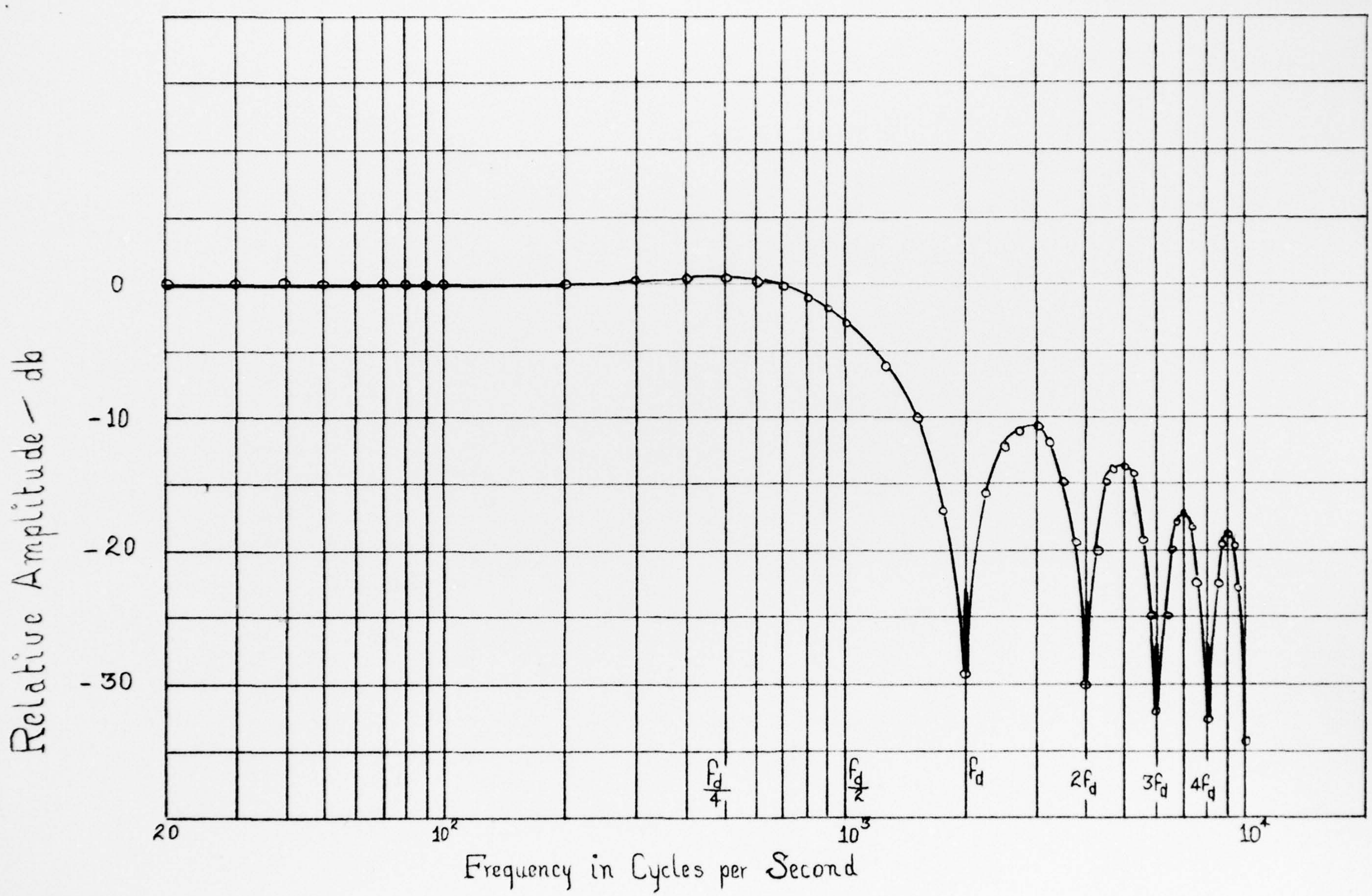


Fig 1 PRNG Output Spectrum; f_d = driving frequency

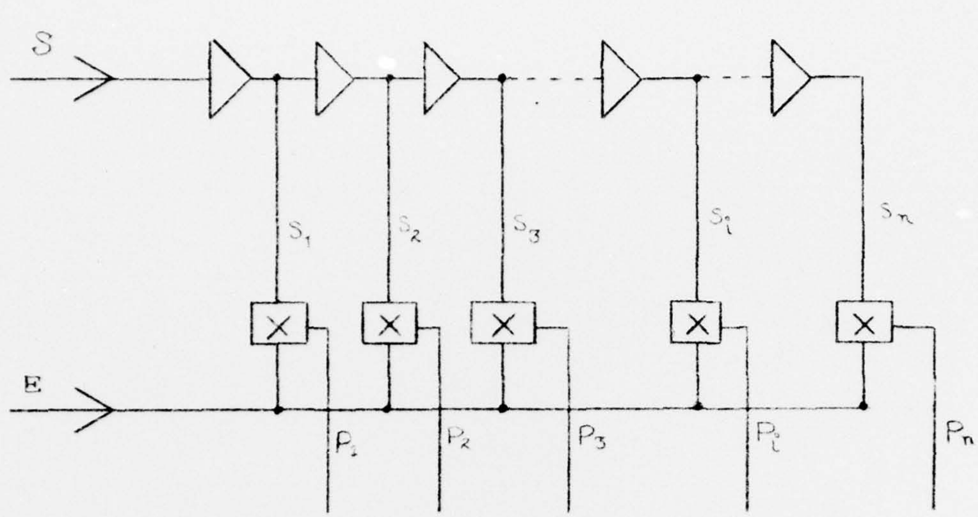


Fig 2a Multiple Correlator

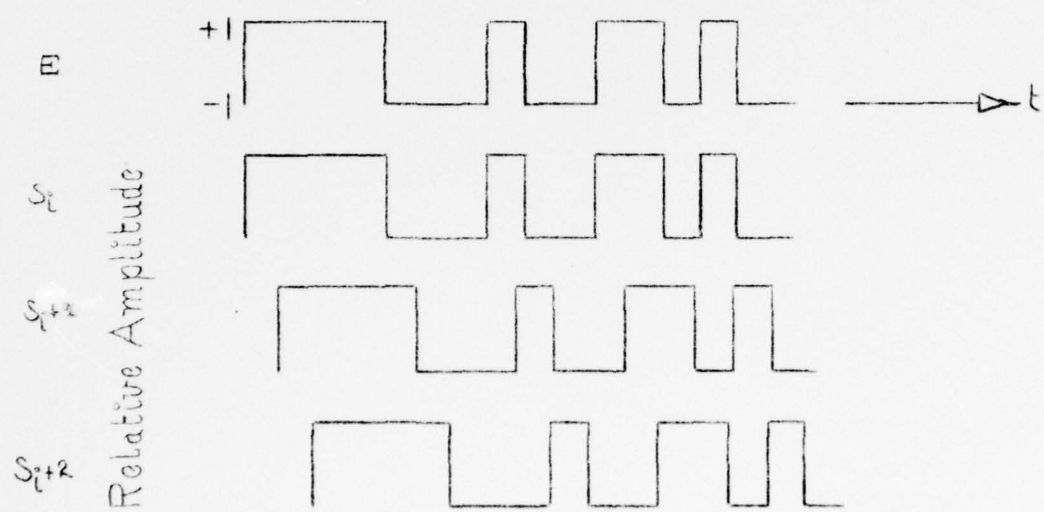


Fig 2b Received Signal and Delay Tap Outputs

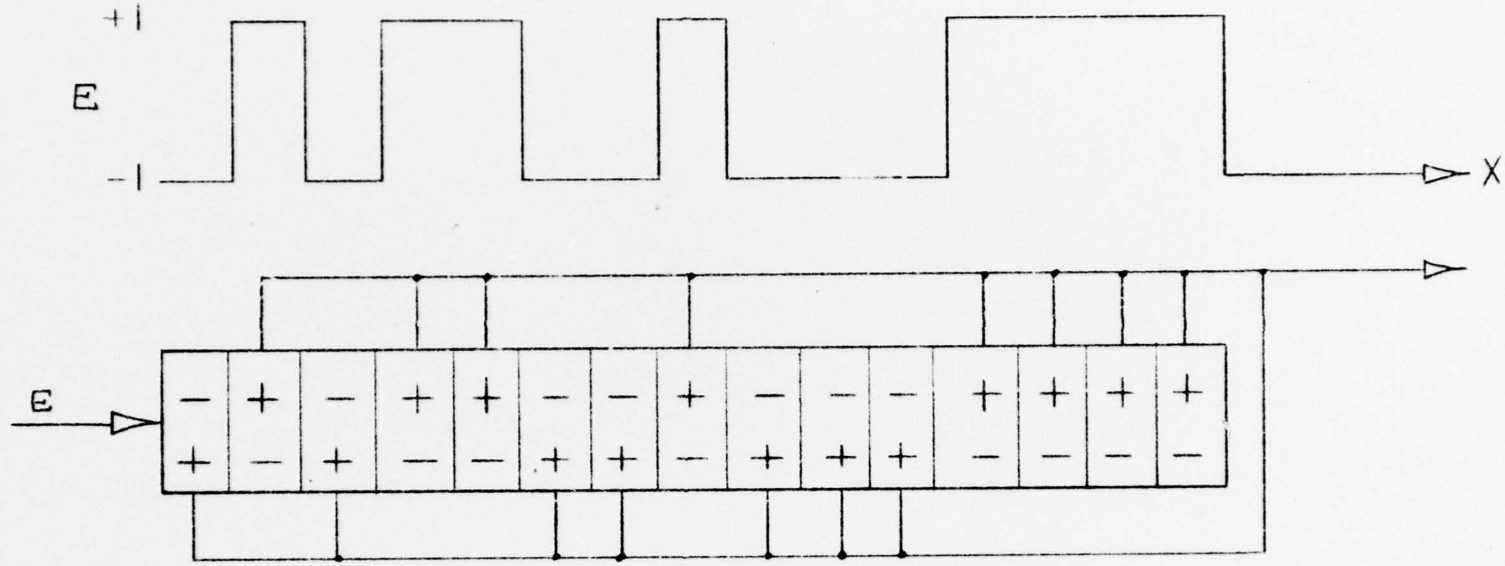


Fig 3 Signal E Synchronized in Matched Filter

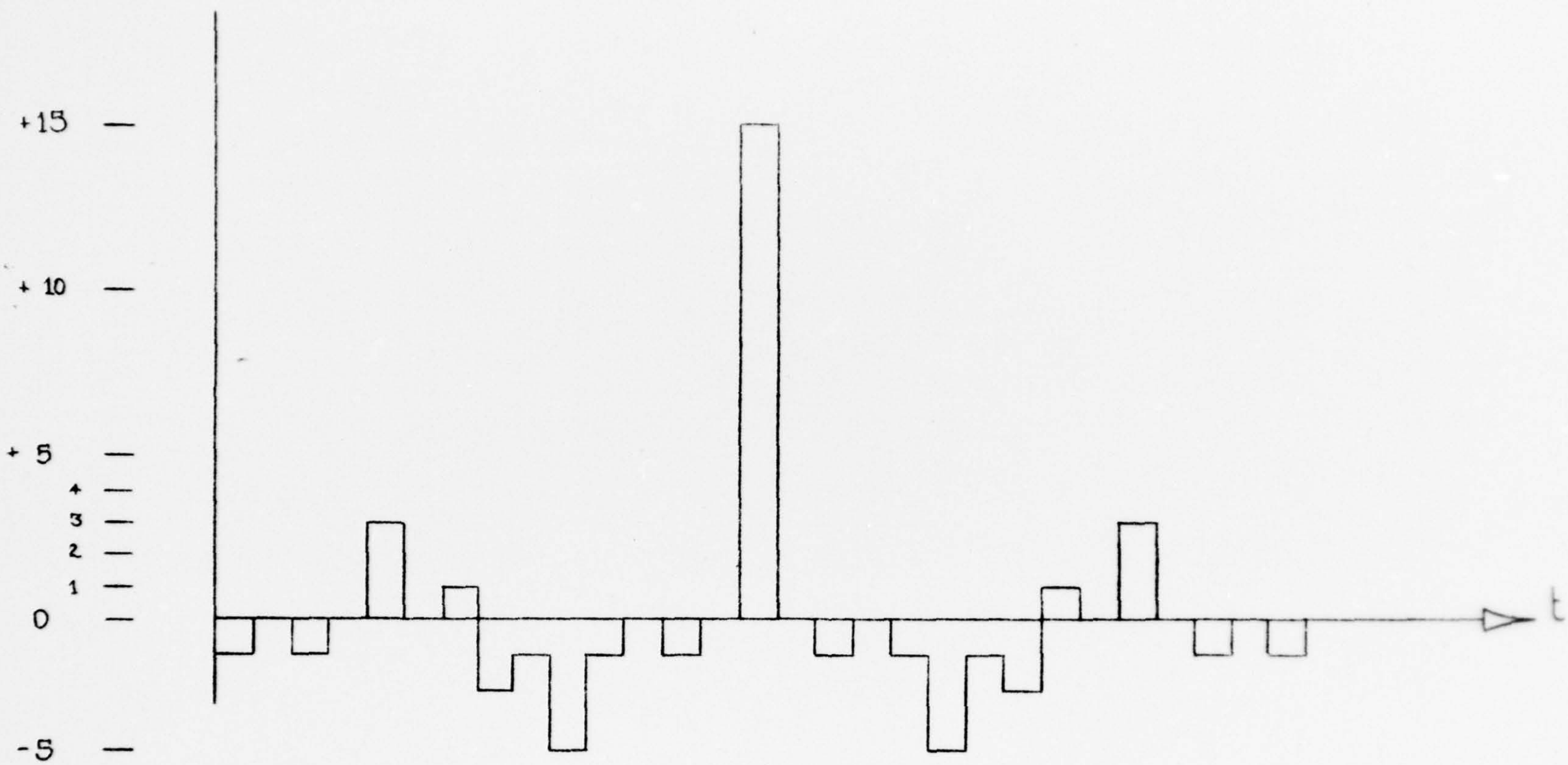


Fig 4 Output From Matched Filter With +1, 0, -1 Possible States Operating on Signal From 4 Stage PRNG

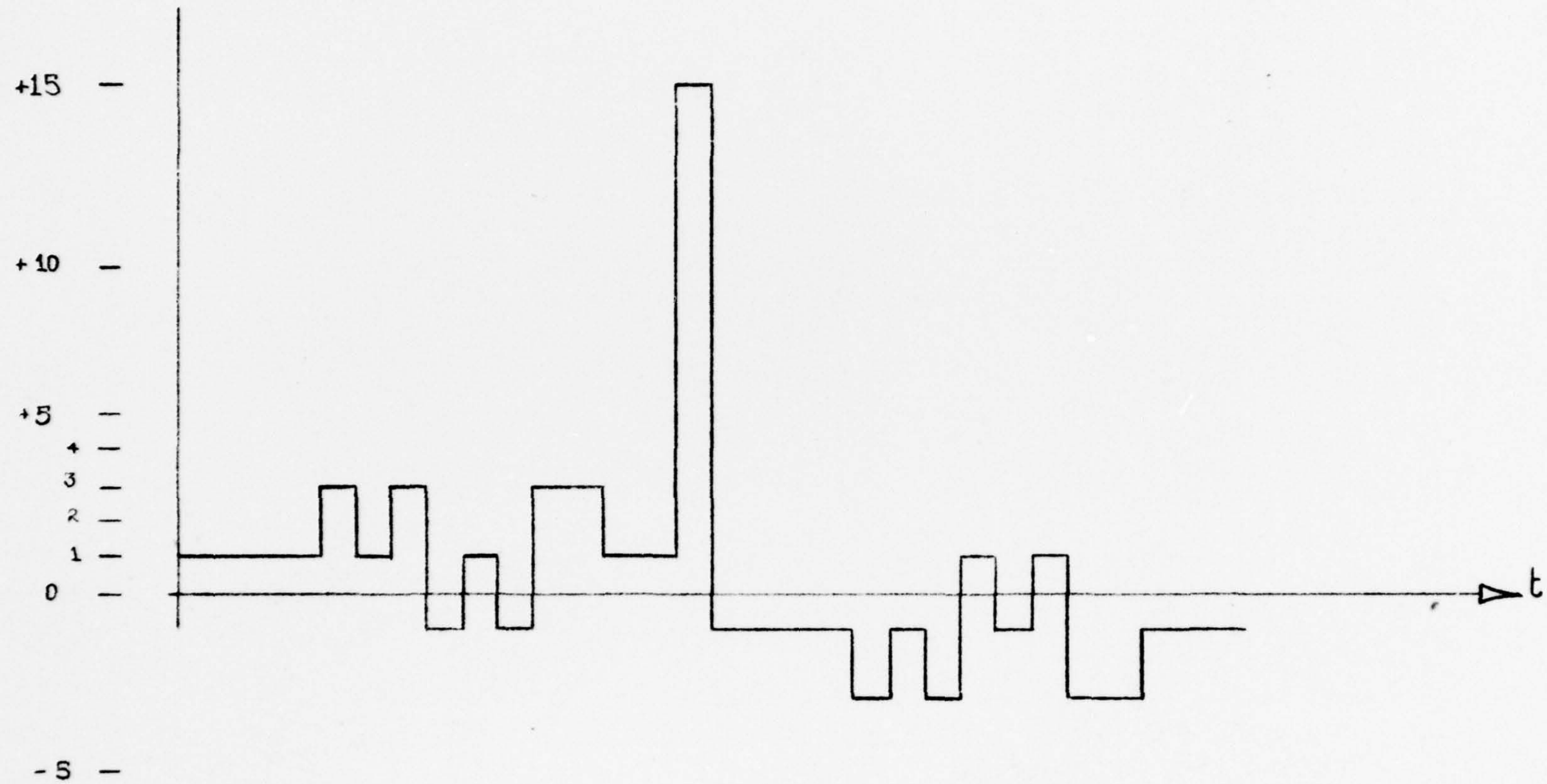


Fig 5 Output From a Digital Shift Register Matched Filter

With +1, -1 Possible States; Signal From 4 Stage PRNG

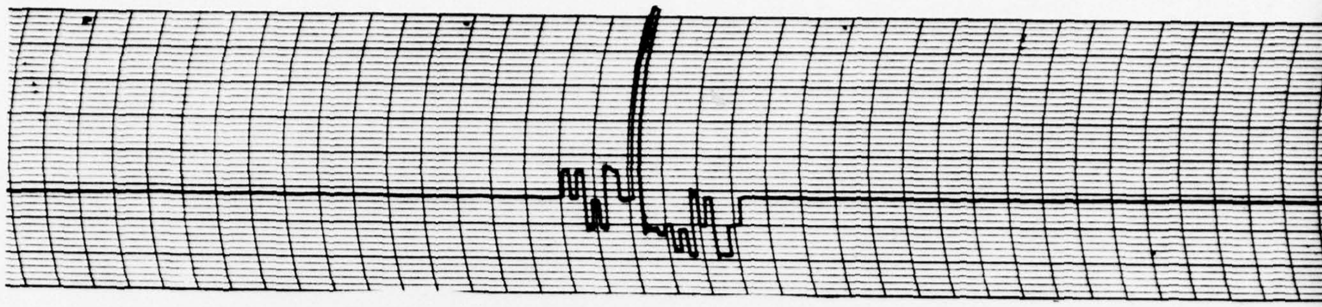


Fig 6a Single sequence filter preloaded with +1's

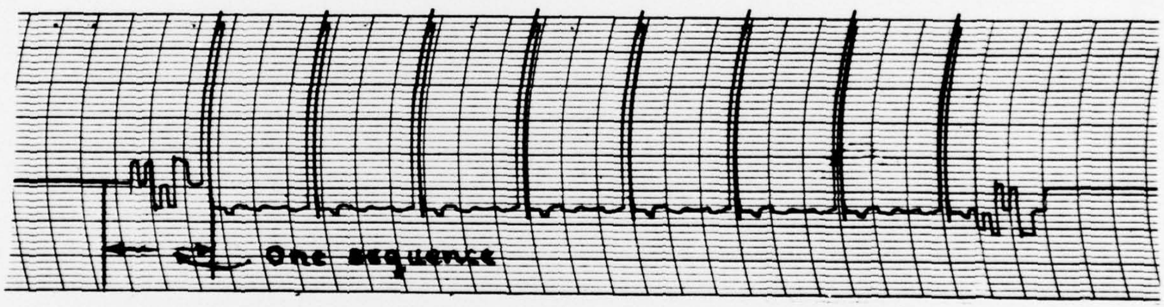


Fig 6b A series of 8 sequences

Fig. 6 Filter Output

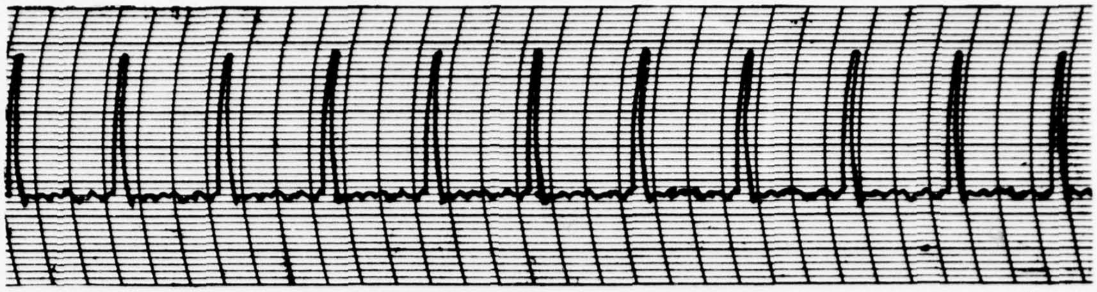


Fig 7a

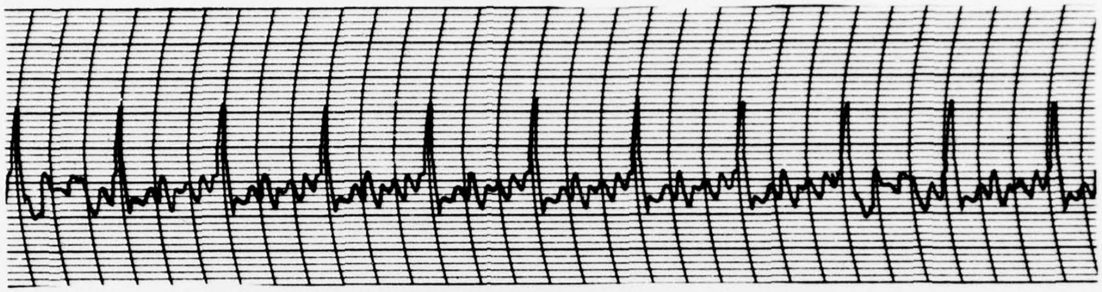


Fig. 7b

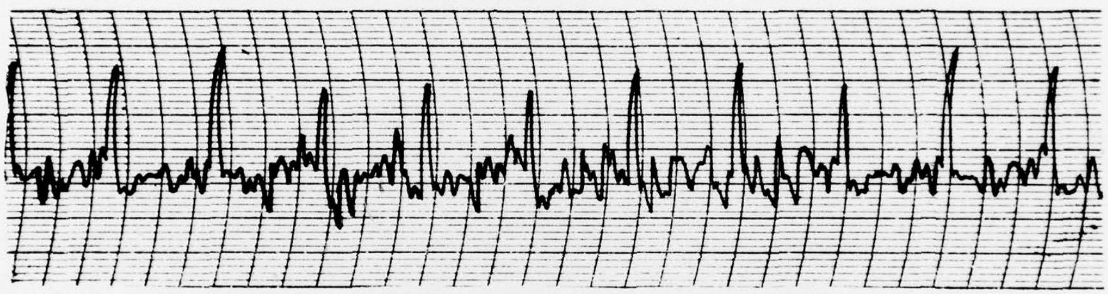


Fig. 7c

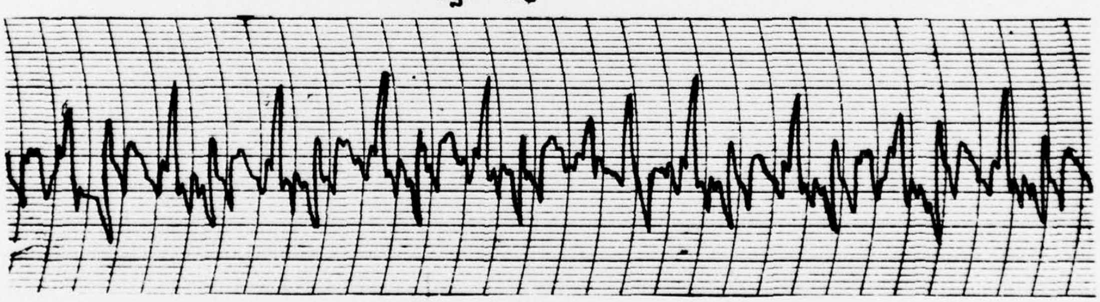


Fig. 7d

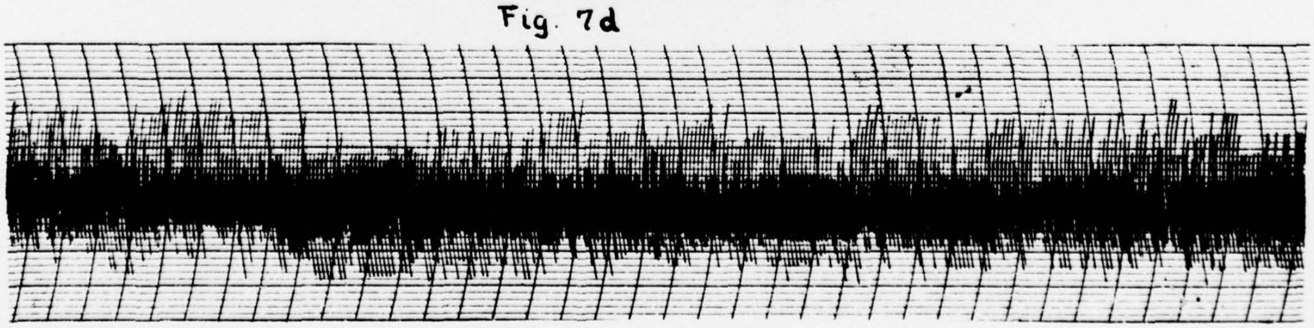


Fig. 7e

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Fig. 7 Typical results with noise + multipaths in modulation system

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